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As this expression is independent of  $c$  and  $\alpha$  the function  $f$  does not contain the quantity  $K$ , and it only involves  $L$  and  $G$  in the form  $2mL - G^2$ . We can best express this by writing the function with variable  $2mL - G^2$ , instead of  $L$ ,  $G$ , when it becomes  $B = f(2mL - G^2, H)$ . If we introduce again into this expression the general values given in equations 11 to 14, we see that the two variables in the function are quite independent of each other if  $c$ ,  $\alpha$ ,  $\beta$  are to have all possible values. And since  $B$  is constant for all values of  $c$ ,  $\alpha$ , and  $\beta$ , it is so for all values of  $2mL - G^2$  and  $H$ , and is therefore absolutely constant. The distribution of *vis viva* is therefore obtained.

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XXII. *The Fusion Constants of Igneous Rock.*—Part II. *The Contraction of Molten Igneous Rock\* on Passing from Liquid to Solid.* By CARL BARUS†.

[Plate V.]

INTRODUCTORY.

1. **MATERIAL and Method.**—The following volume-measurements were made for Mr. Clarence King, on a typical sample of diabase which he furnished.

The method of testing the volume-behaviour by allowing the rock to expand in a vertical tube provided with an index was suggested to Mr. King by Lord Kelvin. I therefore preferred it to a method of my own‡, in which the behaviour in question is to be determined by high-temperature air-volumetry, with the rock enclosed in a *glazed* platinum bulb-and-stem arrangement. In place of the index or float I employed an electric micrometer, believing a probe of this kind to be more trustworthy (§ 13). I may state here, that the fact that the contraction of the magma in passing from liquid to solid can actually be measured by the simple burette method was to me a great surprise. After many trials I found, however, that by allowing the furnace to cool so *slowly* that the platinum vessel remained rigid relatively to the charge, the contraction of the latter could be followed even into the solid state. As a consequence of slow cooling, moreover, the magma was probably undercooled, and I thus obtained the whole volume-difference liquid-solid at a given temperature. The data are

\* Cf. note in American Journal, xlii. p. 498 (1891).

† Communicated by the Author.

‡ Cf. Phil. Mag. July 1892, where this method is tentatively employed to measure the expansion of white-hot porcelain.

sufficient to compute the corresponding contraction at other temperatures.

2. *Literature.*—The question has elicited voluminous discussion; but literary comments are superfluous here, since Prof. F. Niess\*, of Hohenheim, not long ago made a careful survey of all that has been done on the subject. The reader desiring specific information is referred to this interesting pamphlet. “Es ist ein durch Contraste buntes Bild,” says Prof. Niess (*loc. cit.* p. 36), “welches in der vorstehenden Citatenlese dem Leser zu entrollen war, und aus dem Wirrwarr entgegengesetzter Ansichten heben sich nur zwei Körper: Wismuth und Eisen, heraus, über welche man wohl mit absoluter Sicherheit die Acten als geschlossen bezeichnen kann, und zwar in dem Sinne, dass für sie die Ausdehnung im Momente der Verfestigung als zweifellos bewiesen gelten kann. Die übrigen Metalle stehen noch im Streit, und für sie gilt dasselbe was wir für die künstlichen Silicate zu fordern hatten . . . . .” Now iron, in virtue of the occurrence of recalescence (Gore, Barrett), is scarcely a fair substance to operate upon; and it heightens the confusion to find that Prof. Niess, after weighing all the evidence in hand, is obliged to conclude that rocks expand on solidifying.

The present experiments show beyond question, I think, that at least for diabase this is not true. I find that this rock not only contracts between 3·5 and 4 per cent. on solidifying, but that such solidification is sharply broken and only apparently continuous with temperature, and that the fusion-behaviour throughout is quite normal in character. Hence, with certain precautions which I shall adduce in the course of this paper (§ 21), the volume thermodynamic relations which I derived by acting on organic bodies may be applied to rock magmas.

3. *Effect of Fusion. Density.*—The rock after fusion is changed to a compact black obsidian, and quite loses its characteristic structure. It was therefore important to examine the volume-relations of this change, preliminarily. This is done in Table I., where the densities obtained with lumps of the rock (mass  $M$ ) at the temperature  $t$  are given,  $\Delta$  being the density before,  $\Delta'$  after fusion.

\* “Ueber das Verhalten der Silicate etc.,” *Programm zur 70. Jahresfeier d. k. Würtemb. landw. Academie*, Stuttgart, E. Koch, 1889. Cf. Niess u. Winkelmann, *Wied. Ann.* xiii. p. 43 (1881); xviii. p. 364 (1883).

TABLE I.—Density of Diabase before and after Fusion.

Before Fusion.				After Fusion.				
Sample No.	M.	t.	Δ.	Sample No.	M.	t.	Δ'.	$\frac{\Delta - \Delta'}{\Delta}$
I.	<sup>g</sup> 22·8950	°C. 25	3·0161	*I.	<sup>g</sup> 69·9330	°C. 21	2·7018	·104
II.	45·3654	21	3·0181	†II.	33·7659	19	2·7447	·090
III.	54·7208	21	3·0136	+III.	29·9777	19	2·7045	·103
IV.	69·4940	21	3·0235					

The rock was fused both in clay and in platinum crucibles. In the latter case the density of the known mass of metal had been previously determined, and the glass was not removed from the crucible. In the other case the clay was broken away from the solid lump within, and its density then measured directly. A few small bubbles were visible on the fresh fracture of the glass, due, I presume, to the ejection of dissolved gases on solidification. At some other time I will make vacuum-measurements of the density of powders both of the rock and the glass, but I do not believe the data of Table I. will be seriously changed by such a test.

From Table I. it appears that the mean density of the original rock is 3·0178; that of the glass after fusion is only 2·717, indicating a volume *increment* of 10 per cent. as the effect of fusion. This remarkable behaviour is not isolated. Niess (*l. c.* p. 47), quoting from Zirkel's *Lehrbuch*, adduces even more remarkable volume-increments of the same nature‡; viz., in garnet 22 per cent., in vesuvianite 14 per cent., in orthoclase 12 per cent., in augite 13 per cent., &c.: but I doubt whether the great importance of these facts has been sufficiently emphasized. Suffice it to indicate here that it makes an enormous difference into what product the magma is to be conceived as being solidified; and that throughout this paper the molten rock solidifies into a homogeneous obsidian. I am only determining, therefore, those volume-

\* Fused in a clay crucible. Glass detached when cold.

† Fused in a platinum crucible. Glass not detached.

‡ Cf. Thoulet, *Ztschr. f. Kryst. u. Mineralogie*, v. p. 407 (1881); *Bull. Soc. Min. de France*, iii. p. 34 (1880).

changes which lie at the margin, as it were, of the more profound and chemically significant volume-changes (polymeric passage from homogeneity to organized rock-structure), even though the latter may be conceived as producible by pressure alone, under conditions of nearly constant (high) temperature. I may add, in passing, that the magnitude of the chemical changes of volume makes it advisable to carry the work on the effect of pressure on the chemical equilibrium of solids and of liquids, and on the solution behaviour solid-liquid, into greater detail than I have thus far attempted\*.

#### APPARATUS.

4. *Temperature Measurement.*—In work of the present kind an apparatus for the accurate measurement of high temperatures is the fundamental consideration. I may, however, dismiss this subject here, since I discussed it in the introductory paper†. The temperature-measurements of this paper were made with a thermocouple of platinum and platinum with 20 per cent. of iridium, which had been frequently compared with my re-entrant porcelain air-thermometer throughout an interval of 1100° C., and tested for freedom from anomalies beyond this interval. Inasmuch as the electric method consists in expressing thermoelectromotive force by aid of a zero method, in terms of a given Latimer-Clark standard cell, the temperature-apparatus is of the same order of constancy as to time as the standard cell.

To find in how far my earlier data were trustworthy after the lapse of upwards four years, I made fresh check measurements of the boiling-points of mercury and of zinc. The latter only need be instanced here. My original mean datum of the boiling-point of zinc, expressed as electromotive force for the couples under consideration, was (1887)  $e_{20}=11,074$  microvolts, the cold junction being at 20° C. The new experiments (1891) gave me data as follows:—

Thermocouple No. 35,	$e_{20} = 11,168$	(microvolts),
"    No. 36,	"    11,127	"
"    No. 39,	"    11,116	"
"    No. 40,	"    11,136	"
<hr/>		
Mean . . .	11,137	"

\* American Journal, xxxvii. p. 339 (1889); *ibid.* xxxviii. p. 408 (1889); *ibid.* xl. p. 219 (1890); *ibid.* xli. p. 110 (1891); *ibid.* xlii. p. 46 *et seq.* (1891). Also Phil. Mag. [5] xxxi. p. 9 (1891).

† See this Magazine, July 1892, p. 1.

agreeing very closely with subsequent specially careful measurements, viz.:—

Thermocouple No. 36,  $e_{20} = 11,131$  (microvolts),  
 „ No. 39, „ 11,134 „

The difference of values, new and old, is 60 microvolts, only about  $\frac{1}{2}$  per cent. as regards electromotive force, and corresponding to about  $4^\circ$  at  $1000^\circ$ . In view of the excessive use and abuse to which the couples had been put in the lapse of time this result is gratifying.

Endeavouring to ascertain where this discrepancy was to be sought, I also made new comparisons between the Clark cell and a normal Daniell of my own (Bull. 54, U. S. Geolog. Survey, p. 100), in which the cells are separate, and only joined during the time of use. Supposing the electromotive force of the former to have been  $e=1.435$  throughout, the following succession of values obtained for the standard Daniell:—

March	1886, $20^\circ$ C.,	$e=1.138$ ,
August	1887, $28^\circ$ C.,	1.139,
September	1891, $27^\circ$ C.,	1.147.

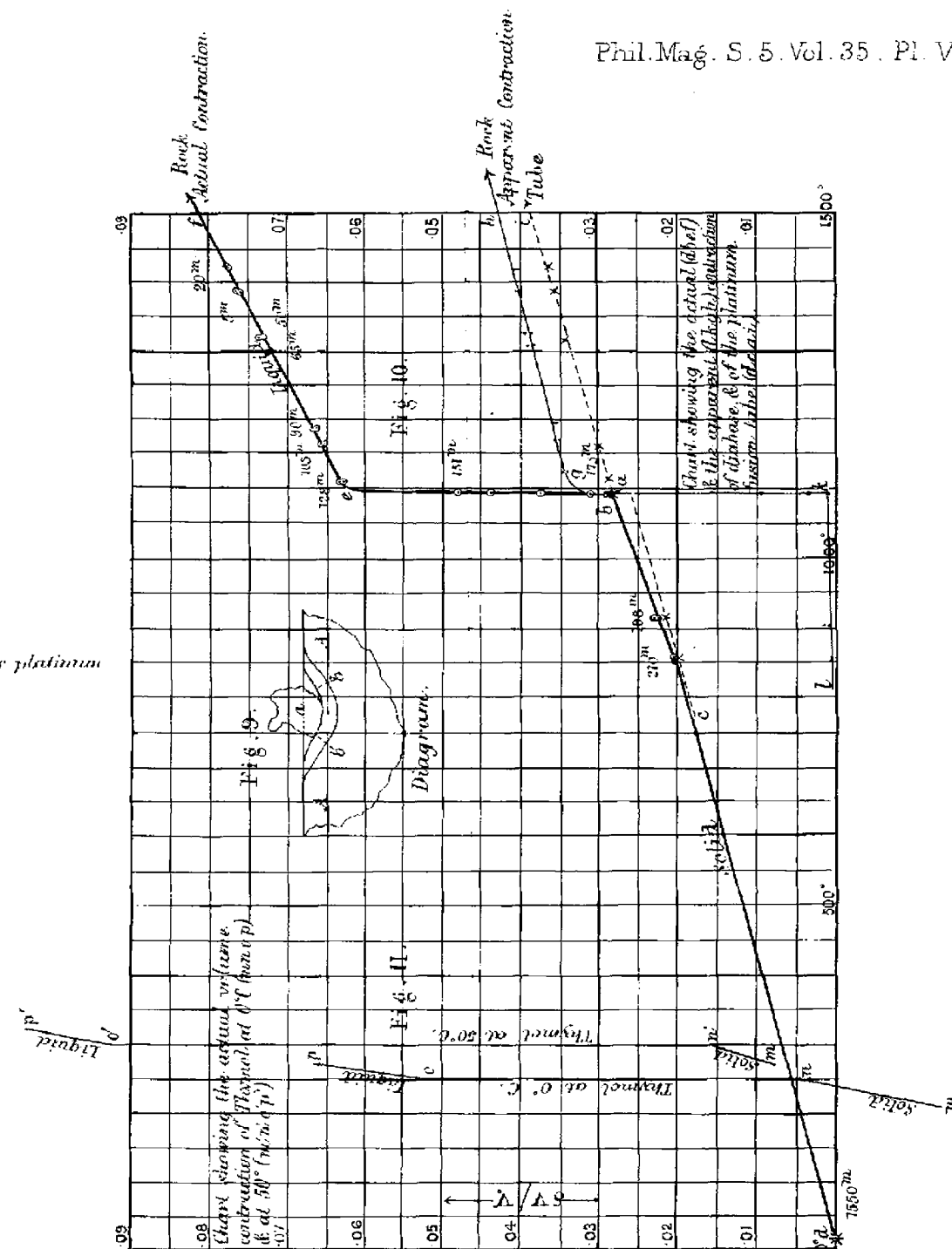
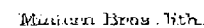
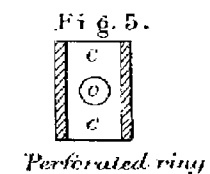
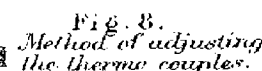
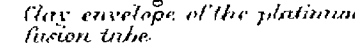
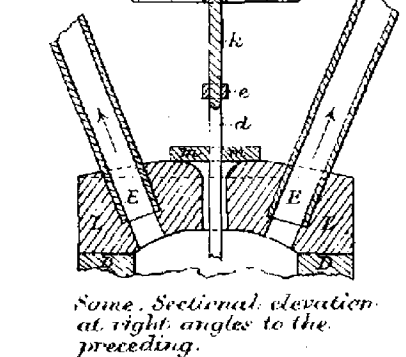
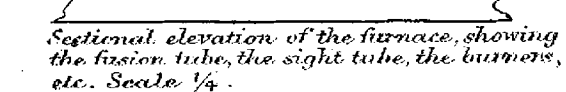
If, therefore, instead of regarding the Clark cell as constant I had attributed\* this virtue to the standard Daniell, the small thermoelectric discrepancy equivalent to  $4^\circ$  at  $1000^\circ$  would be altogether wiped out. Now I made the Clark cells in question as far back as 1883, when less was known about details of construction than is now available. I conclude, therefore, that the discrepancy is very probably in the standard cells, and that the thermocouples have remained absolutely constant, a result which is borne out by my boiling-points of cadmium.

Apart from this, the new standardization with boiling zinc fixes the scale relatively to the accepted value for this datum.

5. *General disposition of Apparatus.*—This is given in Plate V. on a scale of 1 : 4, where figs. 1 and 3 are sectional elevations showing the parts chiefly with reference to their vertical height, and fig. 2 is a sectional plan, in which the parts are given with reference to the horizontal.

The molten rock, Z Z, contained in a long cylindrical platinum tube, largely surrounded by a tube of fire-clay, F F, is fixed vertically in a tall cylindrical furnace, D D, L L. The heat is furnished by six burners, B, B, . . . , fed by gas and an

\* Our laboratory affords insufficient facilities for the direct measurement of electromotive force.



air-blast, laden, if need be, with oxygen. These burners are placed at equal intervals along the vertical, three on one side and three on the other (see fig. 2), and set like a force-couple, so as to surround the platinum tube with a whirlwind of flame. Suitable holes are cut in the walls of the furnace for the symmetrical insertion of the insulated thermocouples, T, and also at S for fixing the sight-tubes, A, near the top and the bottom of the furnace. Parts of the envelope of the platinum tube are cut away, so that the upper and lower ends of the (red hot) platinum tube can be seen in the telescope of an external (screened) cathetometer. Thus the expansion of the platinum tube is measured directly. A vertical micrometer, *Kkd* (figs. 3 and 4), insulated so as to admit of electrical indications of contact, furnishes a means of tracing the apparent expansion of the rock *ZZ*, within the fusion-tube.

In principle, the excessively slow cooling of the furnace is to be so conducted that the magma may always remain much less viscous than the practically rigid platinum envelope (§§ 1, 18).

The furnace stands on a massive iron base perforated by eight holes, into which vertical iron uprights are screwed, symmetrically surrounding the furnace and at a distance of 4 or 5 centim. from its circumference. Only one of these is indicated at *QQ* (fig. 3), the rest with other subsidiary parts being omitted to avoid confusing the figure. Two of these uprights hold the vertical micrometer, two hold the burners in place, and two subserve as buffers for the clay arms, *H, H, ...* by which the fusion-tube is adjusted vertically. The sight-tubes are suitably clamped to the seventh and the insulators of the thermocouples to the eighth. All these uprights are hollow, and a swift current of *water continually circulates* through them, issuing still cold to the touch. The same current also flows through the bent screen, *XX*, of the vertical micrometer, and through the vertical flat screen of the cathetometer.

6. *The Furnace.*—The burners, *B*, are each fed with the same amount of gas and air by properly branching the large supply-tubes. A graduated stopcock is at hand for regulating the supply of gas to a nicety. Hence the furnace is fed with a mixture of gas and air, and temperatures between 400° and 1500° are obtained by simply making the influx poorer or richer in combustible gas. Oxygen has not thus far been necessary\*.

- \* Burners suitable for the above purpose are shown in my little book on high temperatures (Leipzig, Barth, 1892).



The products of combustion are carried off by the two oblique tubes, E, E, in the lid L L (fig. 4). Note that the water-screen bends around the vertical micrometer in such a way that flames issuing from E do no injury, and a perforated free plate, *mm*, closes the vertical hole in the lid L L.

Two large size Fletcher-bellows, set like a duplex-pump and actuated by a gas-engine, furnished the air-blast.

In order to insure greater constancy of temperature, and at the same time increase the high temperature efficiency of the furnace, it is essential to jacket both the latter and the lid heavily (1-2 centim.) with asbestos.

7. *Fusion-tube*.—The platinum tube holding the molten rock Z Z is 25 centim. long and about 1.5 centim. in diameter, drawn as accurately cylindrical as possible and provided with a flat bottom. To protect this tube from gases, to keep it from bulging in consequence of the fluid-rock pressure within, and to insure greater constancy and slower changes of temperature, the platinum tube is surrounded by the fire-clay tube F F (figs. 1 and 6) fitting loosely. Care must be taken to allow for shrinkage of the clay, which in a fresh tube, after some hours' exposure to 1500°, exceeds 3 per cent. or more, and is permanent. After this the tube expands normally. It rarely warps, and may therefore be fixed by fire-clay arms, H (figs. 1, 2, and 7), suitably clamped on the outside of the furnace. Near the bottom a perforated ring, C C (figs. 1 and 5), embraces both the tube F F and a projection, G, in the furnace.

8. *Thermocouples*.—In addition to figs. 1 and 2, figs. 6 and 8 give a full account of the adjustment. The tube F F is laterally perforated with three pairs of fine holes, *t*, corresponding to the two canals of the insulator\*, T T. The wires of the thermocouple are then threaded through *t* and the insulator canals, in such a way that the respective junctions lie in small cavities at *t*, immediately in contact with the outside of the platinum tube. Holes are left in F F and the furnace for this operation.

The cold junctions of the thermocouples terminate in three pairs of mercury-troughs, insulated by hard rubber, and submerged in a bath of petroleum. With these troughs the terminals of the zero method are successively connected, and the temperatures of the top, the middle, and the bottom of the fusion-tube measured by § 4.

\* The method of making these is given in Bull. No. 54, U. S. Geolog. Survey, p. 95.

9. *Sight-tubes*.—Grunow's excellent cathetometer is placed on a pier, so that the prism of the instrument is only about 50 centim. off from the fusion-tube. A tall, hollow screen, 30 centim. broad, 70 centim. long, and 1 centim. thick, fed with cold water, and movable on a slide, is interposed between furnace and cathetometer. Slots, cut through the screen and closed by plate glass, correspond to the two positions of the telescope; and the lines of sight pass through S, S, near the top and the bottom of the furnace (see figs. 1 and 2). Thus the ends of the fusion-tube, one of which projects above the clay tube F F, and the other is seen through the perforation O in C C (figs. 1 and 5), appear as sharp lines in the telescope, against the red-hot background of clay.

It is necessary, however, to prevent the escape of flame and gas at S, and hence these holes are provided with porcelain tubes A (only one shown in the figure) about 15 centim. long, the outer end of which is ground off square and closed with a piece of plate glass *b*, by aid of a clamping device *aa*.

10. *Vertical Micrometer*.—Figures 3 and 4 give a full account of this instrument (also made by W. Grunow), both of which are sectional elevations at right angles to each other. The millimetre-screw plays easily through the massive block of brass, P P, and the fixed lock-nut *gg*. P P is bolted down to the rigid bridge of brass, N N, by means of screws, R R, and the counterplate U U. The ends of N N are provided with sleeves, *p p*, and a clamp-screw, M, whereby the whole micrometer may be moved up or down or fixed in any position along the uprights, Q Q. To secure insulation of the screw K *k*, R, R are surrounded by jackets *n, n* of hard rubber, and plates, *i, j, q* of this material are suitably interposed between P P, N N, U U, and other parts.

Sufficiently wide slots are cut in the bridge, N N (see figures), whereby the plate may be shifted in any direction, and then clamped in position.

In view of the heat which rises from the furnace, an N-shaped screen, X X, through which water rapidly circulates (entering and leaving at diagonally opposite points, V and Y, at the top), nearly envelopes the micrometer. The micrometer-screw passes through a narrow tube in the bottom of X X; hence the screen must also be adjustable, and a way is shown in the figure. Thus the micrometer and its water-screen slide as a single piece, along the upright Q Q. Q and Y are joined by a sufficient length of rubber hose, a connexion merely indicated in the figure.

Finally  $K$   $k$  is prolonged by a straight cylindrical tube of platinum  $d$   $d$ , which may be fixed to the steel rod  $k$  by the clamp  $e$  in any position along the vertical. The tube fits the rod  $k$  singly, and a special steel rod is provided by which the tube may be straightened, should it become warped.

The lower end of  $d$  is clearly visible in the telescope of the cathetometer, through the sight-tube  $A$ . On being screwed down,  $d$  enters the fusion-tube axially, supposing both tubes ( $d$  and  $Z$   $Z$ ) to have been properly fixed in position. In how far such adjustment has been made, can be seen by temporarily removing one of the efflux tubes,  $E$  (fig. 4), when the parts concerned are visible to the eye.

11. *Telephonic Registration*.—Since it is necessary to find the depth of the meniscus of the molten rock  $Z$   $Z$  below the plane of the top of the fusion-tube, the moment of contact of  $Z$   $Z$  and  $d$  is registered electrically. Above, say,  $500^{\circ}$   $C$ ., rock is a good conductor. Hence, if a current be passed into the screw  $K$   $k$ , through the clamp-screw  $f$  (fig. 3), it will issue at the bottom at the clamp-screw  $c$  (fig. 1), provided  $c$  be electrically connected (platinum wires) with the bottom of the fusion-tube,  $Z$   $Z$ .

A telephone actuated by Kohlrausch's small inductor is more convenient for the present purpose than a galvanometer. Contact is then indicated by a loud roar, and the observer's attention is not further distracted. If the glass  $Z$   $Z$  be sticky, the drawing out of a thread corresponds to a more or less gradual cessation of the noise, so that the character of the fusion can be pretty well indicated in this way. Care should be taken to insure a small sparking-distance.

If the expansion of the rock be known, and the tube  $d$   $d$  be sunk deeply into the mass, it is clear that the present method admits of a measurement of the relation of the electric resistance of the glass and temperature. I mention this, believing that not only will a suitable method of temperature measurement be thus available, but that the volume diagrams, constructed below, may also be derived solely from measurements of electrolytic resistance\*.

#### METHOD OF MEASUREMENT.

12. *Consecutive Adjustments*.—Thus far I have only studied rock-contraction. For this purpose, the graduated faucet,

\* Cf. Am. Journ. Sci. xlii. pp. 134–35 (1891), where I have already speculated on the character of electrolytic resistance referred to temperature.

§§ 5, 6, is turned on in full, and the furnace fired as far as 1400° or 1500°, when the measurements may be commenced. The length of the fusion-tube is first accurately measured by cathetometer observations at the bottom and the top. The telescope is then left adjusted for the top, and the vertical micrometer (centrally fixed) screwed down until the image of its lowest point is in contact with the cross hairs. After this the micrometer is further screwed down, until the telephone indicates contact between the platinum micrometer-tube and the meniscus of molten rock. The difference of readings gives the depth of the latter below the top plane of the fusion-tube. I usually repeated these measurements three times.

Hereupon the temperature measurements were made by connecting the terminals of the zero method with the lower, the middle, and the upper thermocouple.

Finally, the cathetometer and micrometer measurements were again repeated in full. Uniform heating presupposed, it was permissible to regard the two sets of length measurements as coincident with the intermediate temperature measurement.

This done, I frequently waited 15 minutes or more, to make another complete measurement, under better conditions of constant temperature.

The graduated stopcock was then partially closed by a proper fractional amount, and after waiting a sufficiently long time, the same series of measuring operations was gone over again. Thus I continued until the glass became sticky and solidification imminent, when longer waiting and more finely graded changes of temperature were essential. Fortunately the observer can infer the state of fusion very well, by noting the time necessary for the glass threads drawn out by the micrometer to break, § 11. Finally, the enamel on the end of the micrometer-tube becomes solid and ceases to change its form, simultaneously with which the marked contraction of the molten mass in the fusion-tube begins.

Having waited long enough for the lowest position of the meniscus, temperature may be varied in larger steps again.

When the furnace is dark, measurement is no longer possible. I then allowed the whole arrangement to cool over night, and next morning determined both the depth of the solid meniscus and the length of the cold tube. The former was computed from bulk measurements (with water) as well as measured micrometrically. These are the normal or fiducial data to which all the other volumes were referred.

13. *Computation.*—Let the linear expansion of the platinum fusion-tube be given by  $l=l_0(1+f(t))$ , where  $l$  and  $l_0$  are the lengths at  $t$  degrees and at zero respectively. Let  $\lambda$  and  $\lambda_0$  be the depths of the meniscus below the plane of the top of the fusion-tube, and  $v$  and  $v_0$  the volumes of the enclosed molten magma at  $t$  and zero respectively. Then, if  $(1+f(t))^3$  is nearly enough  $1+3f(t)$ ; if the expansion constants of the fusion-tube and of the micrometer-tube be the same, and if in consideration of the small motion of the latter and the high temperature in the furnace, the air temperature outside of it be nearly enough zero, since

$$v_t/v_0=(l_0-\lambda)(1+f(t))^3/(l_0-\lambda_0),$$

$$(v_t-v_0)/v_0=3f(t)+(\lambda_0-\lambda)(1+3f(t))/(l_0-\lambda_0). \quad (1)$$

Here  $3f(t)$  is directly given at each observation, or may be computed by some smoothing process from the data as a whole.

The equation, therefore, gives the actual expansion of the rock, in terms of unit of volume of solid rock at zero Centigrade. If this be multiplied by the initial specific volume, the absolute expansion is obtained. An inspection of (1) shows that in the factor  $\lambda_0-\lambda$ , the micrometer value of the length  $\lambda$  is to be inserted in both cases, supposing the contour of the meniscus to remain similar to itself; whereas in  $l_0-\lambda_0$  the value of  $\lambda_0$  determined from bulk measurements of the space at the top of the cold tube is suitable, since the tube is flat-bottomed.

I may add in passing that if  $\delta H$  be the rise of a flat-bottomed cylindrical float of platinum, submerged to a depth  $h$  in a column of magma of height  $A$ , then nearly

$$(v_t-v_0)/v_0=3f(t)+\delta H/(A-h). \quad (2)$$

Since, therefore, the float shortens the efficient length of the fusion-tube and there is difficulty in determining  $A$  in this case, the above micrometric method is preferable quite aside from flotation errors due to viscosity and capillarity, to the easy welding of white hot platinum surfaces, to the tendency of gas bubbles to accumulate on the surface of the float, to the cessation of true flotation during the change from liquid to solid, &c.

14. *Errors.*—The change of temperature from top to bottom of the fusion-tube is measured. The change of temperature from circumference to axis of the fusion-tube is *nil*

in proportion as the furnace cools slowly. The latter condition is met at least so long as glass is liquid, and data for the former are fully given below. To avoid strains of dilatation it would be desirable to make the glass solidify from the bottom upward. This, however, my furnace as yet fails to do. Indeed, I have frequently noted lateral holes shaped like an inverted funnel and terminating in the otherwise smooth surface of the meniscus. This may indicate the occurrence of gas bubbles under the free surface or be a strain effect, § 3. The tendency of these nearly unavoidable difficulties is to make the solidification contraction too small; and I have therefore not been disturbed by them.

Only at very high temperatures (above 1500°) did I obtain apparent evidence of the viscosity of platinum relatively to the pressure of the column of 25 centim. of molten rock, whereas the combined system of platinum and clay tube withstood this pressure. There is also a slight deepening of the meniscus from day to day, and a similar decrease of the length of the platinum fusion-tube; but, thus far, I have encountered no serious error due to the high temperature viscosity of the vessel, § 18.

The assumption that the meniscus remains similar to itself in form at all temperatures cannot be quite true. At white heats, however, the glass wets platinum so thoroughly that convex forms of meniscus need never be apprehended. It is futile, however, to endeavour to make allowance for meniscus; but data for the difference between the (cold) bulk and micro-metric measurements are given below. Although too much reliance must not be placed on the behaviour of the solid state, yet the values are redeemed from the character of mere estimates by the close coincidence of the expansion of platinum and its solid glass core. Strains imposed on both the metal and the glass do not probably exceed the limits of elasticity of either, §§ 17, 18. When cooling is conducted slowly enough, the experiments show that the platinum tube is not dragged along seriously by the solidifying magma; and the data thus retain a degree of trustworthiness greater than was anticipated, even in the solid state. At the same time dilatational strain is reduced to a minimum, and constancy of temperature throughout efficient parts of the furnace is promoted.

One error much in my way thus far has been the allowance to be made for the expansion of the platinum probe *dd* (fig. 3). It is not merely the amount by which the probe is lowered that is subject to expansion, but a considerable length of the

metallic screw *Kkdd* passes from a lower to an indeterminable higher temperature. I hope, however, in the future to obtain an estimate for this discrepancy, by measuring a given amount of thrust through the sight-tube with the cathetometer, and comparing this value with the corresponding value to be read off on the vertical micrometer. Hollow screws and water circulation would be exceedingly difficult to attach here.

# RESULTS.

15. *Arrangement of the Tables.*—In the following tables  $l$  and  $v_0$  denote the length and radius of the (cold) fusion-tube, and  $\lambda_0'$  the bulk value (water measurement) of the mean depth of the meniscus, these measurements being made on the day after the fusion experiments. The temperatures at the bottom, the middle, and the top of the fusion-tube are given under  $\theta_1, \theta_2, \theta_3$ , respectively. For each value of mean temperature  $\theta$ , two data for the apparent expansion of the rock, for the volume-expansion of the fusion-tube, and for the actual volume-expansion,  $(v_t - v_0)/v_0 = \delta v/v_0$ , of the rock are given, and they were obtained before and after the intermediate temperature measurement, respectively. Reference is thus made to unit of volume of solid rock at zero Centigrade, throughout. The data enclosed in parentheses show that for them, the value applied for the expansion of the fusion-tube is obtained as a mean result of all the measurements made, otherwise the value directly observed was directly applied. The chief constants are summarized at the end of each table.

16. *Contraction of Diabase. Series I. and II.*—The results of these series, being of inferior accuracy and serving chiefly to substantiate the remarks of § 14, may be omitted here. They showed a liquid volume-expansion of  $50/10^6$  per degree, a solid expansion of  $20/10^6$  per degree, and a solidification contraction of about 3 per cent. only, owing to the occurrence of dilatational strain.

17. *Contraction of Diabase. Series III., Tables.*—This work was done on October 20, 1891, and the data are given in Table II. Precautions for slow cooling were fully taken, and the solidification point is therefore sharply apparent. The results will be discussed in connexion with the next series.

TABLE II.—Contraction of Diabase. Series III.

$l_0=25\cdot466$  centim.,  $\lambda_0=1\cdot424$  centim.,  $r_0=.75$  centim.

$\theta_1$ , $\theta_2$ , $\theta_3$ .	Mean $\theta$ .	Apparent volume- expansion of Rock.	Volume- expansion of the tube.	$\delta v/v_0$ .	Mean. $\delta v/v_0$ .	Time.	Remarks.
$^{\circ}\text{C}$ .	$^{\circ}\text{C}$ .	$\times 10^4$ .	$\times 10^4$ .	$\times 10^4$ .		Minutes.	
1360	1386	452	358	810	.0811	0	Liquid.
1396		454	(356)	812	(.0809)		
1403				(808)			
				(810)			
1286	1300	437	340	777	.0778	23	Liquid.
1304		438	(334)	778	(.0772)		
1311				(771)			
				(772)			
1163	1166	406	297	703	.0704	53	Sticky.
1167		409	(300)	706	(.0707)		
1168				(706)			
				(709)			
1097	1093	376	270	646	.0646	86	Very sticky.
1093		333	(281)	603	.....		To be drawn
1089				(657)	(.0657)		out in threads.
				(614)	.....		Eventually
							solidifying.
1102	1095	14	273	288	.0287	111	Solid.
1095		13	(282)	286	(.0296)		
1088				(296)			
				(295)			
929	896	0	211	211	.0212	157	Solid.
897		2		(213)			
863							
461	468	- 4	81	77	.0079	185	Solid.
433		0		81			
510							
	20	0	0	0	.0000	Next day.	Cold.

{	Rock, mean actual expansion, solid, $0^{\circ}$ - $1000^{\circ}$	. . .	.0000250
	"    "    "    "    liquid, $1100^{\circ}$ - $1500^{\circ}$	. . .	.0000470
	"    contraction on solidification ( $1094^{\circ}$ )	. . .	.0390
{	Rock, mean apparent expansion, solid, $0^{\circ}$ $1000^{\circ}$	. . .	.0000007
	"    "    "    "    liquid, $1100^{\circ}$ - $1500^{\circ}$	. . .	.0000205
{	Tube, mean volume-expansion below $1000^{\circ}$	. . .	.0000240
	"    "    "    "    above $1100^{\circ}$	. . .	.0000265

18. *Contraction of Diabase. Series IV. Tables and Chart.*—  
The data of the last series of experiments (made on October 21, 1891) are given in Table III. Two complete sets of results correspond to each step of temperature.



$$l_0 = 25.447 \text{ centim.}, \lambda_0' = 1.220 \text{ centim.}, r_0 = 75 \text{ centim.}$$

$\theta_1$ . $\theta_2$ . $\theta_3$ .	Mean. $\theta$ .	Apparent volume- expansion of Rock.	Volume- expansion of the tube.	$\delta v/v_0$ .	Mean. $\delta v/v_0$ .	Time.	Remarks.
°C. 1374 1394 1395	°C. 1388	$\times 10^4$ . 403 404	$\times 10^4$ . 357 (356)	$\times 10^4$ . 760 761 (759) (760)	·0760 (·0760)	Minutes. 5	Liquid.
1415 1431 1417	1421	407 409	362 (364)	768 771 (771) (773)	·0770 (·0771)	20	Liquid.
1318 1324 1315	1319	394 387	341 (339)	734 727 (733) (726)	(·0731) (·0730)	50	Liquid.
1304 1308 1304	1305	383 390	350 (335)	733 740 (718) (725)	·0736 (·0721)	65	Liquid.
1204 1189 1176	1190	357 355	316 (305)	673 671 (662) (660)	·0672 (·0661)	90	Sticky.
1177 1158 1153	1163	355 349	299 (299)	655 649 (655) (649)	·0652 (·0652)	105	Very sticky. To be drawn out in threads.
1138 1109 1090	1112	339 344	286 (286)	625 630 (625) (630)	·0628 (·0628)	128	Top en- crusted.
1117 1088 1072	1092	200 155 91	275 (280)	475 430 366	·0475 (·0480)	151	Solidifying.
1109 1081 1086	1092	33 5	282 (280)	315 287	·0287 (·0285)	175	Solidifying.
946 903 893	914	13 6	213	226 220	·0223	198	Solid.
900 827 837	855	3 3	199	202 202	·0202	210	Solid.
	20	0	0	0	·0000	Next day.	Cold.

{	Rock, mean actual expansion, solid, 0°-1000° . . .	.0000250
	"    "    "    "    liquid, 1100°-1500° . . .	.0000468
	"    contraction on solidification, at 1092° . . .	.0340
{	Rock, mean apparent expansion, 0°-1000° . . .	.0000005
	"    "    "    "    1100°-1500° . . .	.0000218
{	Tube, mean volume-expansion below 1000° . . .	.0000235
	"    "    "    "    above 1100° . . .	.0000260

These data are given in the chart (fig. 10), temperatures in degrees C., as abscissæ, volume-changes as ordinates. A chart of the same character may also be constructed from Table II., but this is superfluous. In figure 10 the actual expansion of the rock is shown by the heavy line *dcbef*, and the numbers attached to the points of observation indicate the times at which they were made. The apparent expansion of the rock is shown by the light line *lkg h*, where the ordinates of the solid contour are nearly zero. Finally the expansion of the fusion-tube is represented by the dotted line *dca i*. The amount of break at *a*, which is even smaller in Series III., indicates the amount of drag or a shortening of the length of the platinum tube by the solidifying rock within, and furnishes an estimate for the trustworthiness of the solid results. It is interesting to note that in both Series III. and IV. the first length measurements of the tube are smaller than the second at the same temperature, showing that the tube has to some extent recuperated from the strain, or that the amount of end thrust has diminished. It is similarly possible to note the sag as expressed by the cold lengths (25.49 centim. in Series II., 25.47 centim. in Series III., and 25.45 centim. in Series IV.) of the platinum fusion-tube. Finally, the depth of the liquid meniscus at the outset of Series III. and IV., and at about the same temperature, was  $\lambda = .50$  centim. and  $\lambda = .62$  centim., showing enlargement of the bulk of the tube. These changes, which are in part allowed for, show that viscosity introduces no serious discrepancy. Regarding the differences of  $\lambda_0$  and  $\lambda'_0$  the remarks made in § 14 apply.

An inspection of the curve *dbef* as a whole indicates the occurrence of sharply marked solidification at 1093°. This is sufficient evidence to prove that rock-fusion (diabase) is thoroughly normal in type. A method is thus given in which the solidifying-point is determined free from non-intrinsic tests.

Finally, the contraction on solidification, 3.9 per cent. in Series III., and 3.4 per cent. in Series IV., is established, for diabase at least, beyond question. It is to be noted, moreover, that the smaller value (IV.) corresponds to a larger drag during solidification on the platinum tube (*cf.* Tables II. and III.). Hence the value 3.9 per cent. is the more probable. In general, temperatures ( $\theta_1, \theta_2, \theta_3$ ) are nearly alike so long as the glass is liquid. This ceases to be the case after solidification; and since the top of the fusion-tube is apt to be colder than the bottom, some of the solid contraction expresses itself in dilatational strain, § 14.

19. *Flotation*.—Naturally I made a few tests on the flotation of solid rock on the molten magma. Cf. § 3. To my surprise such flotation usually occurs, notwithstanding the fact that the original cold rock may be 8 per cent. + 10 per cent. more dense than the molten magma. The cause, however, is crudely mechanical, since the rock, in virtue of its weight and temperature, hollows out a cavity and chills its surface simultaneously, forming a little boat in which it floats on the very viscous liquid below. This is indicated in fig. 9, where *a* is the body of rock, AA the molten magma, and *bb* the solidified skin. I also attempted to make Niess and Winkelmann's "Fundamentalversuch" (Niess, *l. c.* p. 16), by submerging the rock; but here, both on account of the intense white glare of the furnace and the tendency to chill at the surface, I did not reach a definite point of view.

#### INFERENCES.

20. *Hysteresis*.—In the above experiments I have only studied the solidifying magma. It does not appear, therefore, whether solidification and fusion take place at identical temperatures, or whether they will comprehend a volume-lag.

In other work, in which the rock of the fusion-tube was alternately fused and solidified, the loci are cyclic in marked degree, covering considerably more than 50°. It is so difficult, however, to discriminate between true hysteresis and the accompanying discrepancy due to insufficiently rapid heat conduction as compared with the insufficiently slow change of temperature, that experiments made with a tube which is not at quite the same temperature throughout its length are not unassailable. Having failed to perfect the experiments, I omit the data altogether.

21. *Melting-point and Pressure*.—Since the fusion of rocks like diabase is thoroughly normal, it follows that melting-point must increase with pressure. It is well to examine tentatively into the nature of this relation, and for this purpose I have constructed certain unpublished results of mine for thymol, in the same scale as used for the rock, in fig. 11. The curve *m'n'o'p'* shows the contraction of thymol at its melting-point (somewhat below 50°), where the substance is liquid along *o'p'* and solid along *m'n'*. The curve *mno p* similarly applies at 0° C. It is seen, therefore, that here solidification contraction and thermal expansion (solid or liquid) decrease together. This is also true on passing from thymol to the rock. Could liquid thymol be cooled down as far as -25°, it would then show the same solidification contraction as the silicate.

Analogously the latter must show decidedly smaller compressibility than the organic body, and hence it follows that whereas the lower critical pressure (solid-liquid) of naphthalene, for instance, lies in the region of some 10,000 atmospheres in my experiments, the corresponding (critical) pressure of the rock magma will be indefinitely higher.

From this, however, it is by no means to be inferred that the relation of melting-point to pressure ( $d\theta/dp$ ) will be different in the silicate and in the carbon compound. In the latter case data for normal fusion are available for wax, paraffin, spermaceti, and naphthalene. These lie within a margin of .020 to .036. Taken into consideration with the difficulty of obtaining these data, the preliminary character of the experiments, the lack of crystalline definiteness in many of the compounds, and the fact that even for the same substance\* the coefficient may vary as much as .027 to .035, the said margin may reasonably be regarded as narrow. It appears to me probable, therefore, since fusion in the organic bodies and the silicate is alike in type, that the same factor  $d\theta/dp$  will correspond to both cases.

Direct evidence in favour of this view will be adduced in my next paper.

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XXIII. *On a certain Asymmetry in Prof. Rowland's Concave Gratings.* By DR. J. R. RYDBERG, *Docent of Physics at the University of Lund, Sweden* †.

I. **I**N order more especially to obtain a series of observations fitted for a continuation of the studies on the spectra of the elements, of which the commencement has been published in my "Recherches sur la constitution des spectres linéaires des éléments chimiques" (*K. Svenska Vetensk. Akad. Handl.* Bd. xxiii. No. 11), a spectroscope with one of Prof. Rowland's concave gratings (10,000 lines to the inch) was procured for the Physical Institution of the University of Lund. It was mounted in a most excellent manner by the Mechanician of the Physiological Institution, Hilding Sändström, according to the instructions of Prof. Rowland (*see* Ames, Johns Hopkins University Circulars, viii. No. 73, May 1889; *Phil. Mag.* [5] xxvii. p. 369), but with full freedom in the details of construction. The adjustments also were executed according to the same instructions, but

\* See my work for Naphthalene in *American Journal*, xlii. p. 144, *et seq.*, 1891.

† Communicated by the Author.